1 The Pursuit of Non-Solar Blind Daytime Raman Water Vapor Lidar Measurements

During IHOP, the SRL demonstrated greatly improved non-solar-blind daytime Raman water vapor lidar measurements over any previously demonstrated. The combination of technologies and techniques that permitted this were 1) a large-pulse tripled Nd:YAG laser, 2) narrow field of view telescope, 3) narrow spectral band detection, 4) fast photomultiplier detectors and 5) a combination of analog and photon counting electronics, which permit the full intensity Raman signals to be sampled. While none of these elements is new, the combination had not been fully exploited previously for Raman water vapor lidar. Furthermore, the path toward this solution was not direct and occurred over more than 20 years of research activity at various research centers.

1.1 The first efforts in Raman water vapor lidar at NASA/GSFC

The first Raman water vapor lidar measurements were made nearly simultaneously in 1969 in separate research efforts by S. H. Melfi [Melfi et. al., 1969] and J. Cooney [Cooney, 1970]. Development of Raman lidar technology for measurement of water vapor was started at NASA/GSFC in 1980 when Dr. Melfi joined the center. The first Raman water vapor lidar system developed at GSFC was based on a QuantaRay DCR1-A tripled Nd:YAG laser (354.7 nm) operating at 10

Hz and providing 150 mj per pulse in the UV. The laser had a single, flash-lamp pumped, amplifier and used harmonic crystals for converting the 1.064 μm fundamental wavelength to the doubled and tripled wavelengths of 532 nm and 354.7 nm, respectively. The crystal housings were not temperature stabilized necessitating tilt-tuning of the crystals to maximize the output energy every two minutes during extended data acquisition periods. The telescope used was based on a 1.5 m searchlight mirror that was built in Japan and used on a German surface ship in World War II. The mirror was found in a military equipment storage facility at Chesapeake Beach, Virginia, moved to GSFC, re-coated and placed into service for use in Raman lidar. A Cassagrain configuration telescope was constructed using this mirror so that the detector package could be installed under the very large telescope. The telescope had relatively poor optical quality so that the received signals were measured using a field of view of 2-5 milliradians. Furthermore, due to uncertainty about whether the substrate material had been annealed, no hole was cut in the mirror so that the return signal were transmitted through the uncoated substrate. A simple detector package consisting of beamsplitters, interference filters and two photomultiplier tubes measuring the Raman signals from water vapor (407.5 nm) and nitrogen (386.7 nm) was used. The interference filters were manufactured by Barr Associates and possessed approximately 15-20% transmission with bandwidths of 5-10 nm. The data system used LeCroy 8837F 8-bit, 32-MHz analog-to-digital (AD) transient recorders and was controlled by a Digital Equipment Computer PDP-11 running the RT-11 operating system. This system was known as the Marine Boundary Layer Ra-

man Water Vapor Lidar and was successfully used to chart the evolution of water vapor in the boundary layer in 1985 [Melfi and Whiteman, 1985]. The system was housed in a mobile trailer and was first used in a field deployment for the Cooperative Huntsville Meteorological Experiment (COHMEX) in Huntsville, Alabama in 1986 [Dodge et. al., 1986] [Fulton and Heymsfield, 1991] [Straka and Anderson, 1993].

The nighttime limitation of this early Raman water vapor lidar system was clear but there was no real progress toward the development of daytime Raman water vapor lidar measurements at GSFC throughout the 1980s despite the fact that the solar blind technique of making daytime Raman water vapor measurements was being demonstrated successfully by others [Renault and Capitini, 1988]. During the 1980s, upgrades to the Marine Boundary Layer Raman Water Vapor Lidar included replacing the searchlight-based telescope with an astronomical quality, 0.75 m aperture system and implementing dual photomultiplier detection channels in a low altitude/high altitude configuration for water vapor, nitrogen and Rayleigh-Mie measurements. The new telescope, although possessing just 1/4 of the collecting area of the former one, significantly improved the signal-to-noise ratio of the measurements due to the greatly reduced losses (both scattering and transmission) and improved focussing quality. The data acquisition system was also upgraded to add photon counting (PC) electronics (Joerger S3 200 MHz counters) to the pre-existing analog detectors [Whiteman et. al., 1992]. The first published measurements of water vapor and aerosol structure of cold and warm frontal passages were made using this system [Melfi et. al., 1989], although the

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measurements were still limited to nighttime.

By the late 1980s, most of the necessary technology was in place to attempt a non-solar blind measurement of daytime water vapor except that interference filter technology still did not permit the fabrication of the high transmission, narrow bandwidth optics that are now available. Furthermore, frequent ground loop and impedance matching problems associated with the simultaneous use of AD and PC measurements encouraged testing the idea of using photon counting electronics exclusively as a replacement for the combined AD and PC system that was in use previously. Two photomultipliers tubes, both operating in the photon counting mode, were used for each measured wavelength. The near range channel was attenuated significantly to permit it to be photon-counted while the far-range channel received the full intensity signal. This concept produced excellent measurements during nighttime tests performed using the Marine Boundary Layer Water Vapor Lidar in 1987. Due to funding limitations in the late 1980s, development work on Raman lidar at GSFC ceased for a period of time and this mobile Raman water vapor lidar was converted into the first mobile stratospheric ozone lidar: STROZ-LITE (Stratospheric Ozone Lidar Trailer Experiment) [McGee et. al., 1991].

1.2 Early Non-Solar Blind Daytime Raman Water Vapor Lidar Activities

The first published measurements of daytime water vapor mixing ratio using non-solar blind Raman lidar were performed in 1991 in northern Germany [Ansmann et. al., 1992] using the narrow field-of-view, narrow spectral band technique being discussed here. The measurements were made

using a high power XeCl laser (>67.5W), 300 MHz photon counting electronics, 0.8 m telescope operating at 0.1 - 0.4 milliradian field-of-view, and grating polychromator providing approximately 0.3 nm bandpass. An additional edge filter was used in the water vapor channel to increase the suppression of the Rayleigh-Mie signal. Due to the low optical efficiency of the system, no atten-uation of the signal was required during daytime measurements to permit the signal to be recorded using only photon counting electronics (private communication, Drs. Albert Ansmann and Ulla Wandinger). Measurements with 10-50% random error were made with this system to an altitude of ~1.7 km using 15 minutes averaging, and ~200 m spatial smoothing.

The need within the atmospheric radiation community to improve the measurements of water vapor and other parameters to support atmospheric radiative transfer modeling led to technology development within the U.S. Department of Energy (DOE) of water vapor measurement systems with improved accuracy and precision [Goldsmith et. al., 1998]. The DOE Instrument Develop-ment Program (IDP) began in 1989 and provided partial funding for the development of the first implementation of the NASA/GSFC Scanning Raman Lidar (SRL). This work was carried out jointly between NASA/GSFC and DOE Sandia National Laboratory (SNL) in a research effort that resulted in the construction of two Raman lidar systems: one at GSFC and the other at SNL. The systems shared the same telescopes and used excimer lasers, but key aspects of the designs were different to explore multiple techniques for making daytime Raman water vapor lidar mea-surements. The NASA/GSFC effort pursued the solar-blind approach for daytime water vapor mea-

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surements and therefore used a fluorine-optimized excimer laser that could operate using either a XeF (351 nm for nighttime measurements) or a KrF (248 nm for daytime measurements) gas mixture. The SNL effort used the narrow-band, narrow field of view approach [Bisson et. al., 1999] and was based on a XeCl laser providing 40-50W of output power. This parallel development effort resulted in the first side-by-side demonstration of Raman water vapor lidar measurements in 1994 [Goldsmith et.al., 1994]. The SNL system later demonstrated the concept of using a large aperture telescope at narrow field of view for improved daytime measurements [Bisson et. al., 1999] and helped to demonstrate some of the concepts that were designed into the DOE CRF (Climate and Research Facility) Raman Lidar, the first automated Raman lidar system [Goldsmith et. al., 1998].

The success of this technology demonstration effort led to the development of a new Raman lidar at the DOE Southern Great Plains (SGP) site in northern Oklahoma [Goldsmith et. al., 1998]. That system, referred to now as CARL (Climate Research Facility Raman Lidar), became operational in 1996 and uses a Nd:YAG laser operating at 9-12W and the narrow-band, narrow-field-of-view approach. CARL's original configuration used only photon counting data acquisition thus requiring a factor of 10 attenuation of the Raman signals during the daytime to prevent photon saturation. Nonetheless, with a 10-min average and 75-m range resolution, water vapor mixing ratio measurements with less than 20% random error to an altitude of approximately 3 km were performed. Several years of such measurements are now available, providing continuous measurements of water vapor throughout the diurnal cycle [Turner and Goldsmith, 1999]. In June

of 2004, the data acquisition system of CARL was upgraded to include both analog and photon counting electronics essentially identical to those in use in the SRL for IHOP permitting the full strength Raman signals to be used during both daytime and nighttime [Ferrare et. al., submitted] [Turner and Goldsmith, 2005].

2 References

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